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TORQUE RIPPLE MINIMIZATION OF INDUCTION MOTOR USING DTC WITH LOW SWITCHING FREQUENCY

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ABSTRACT

DTC of an induction motor fed by a voltage source inverter is a simple scheme that does not need long computation time, can be implanted without mechanical speed sensors and is insensitive to parameter variation. In principle, the motor terminal voltage and current are sampled and used to estimates of the flux position and the instantaneous error in torque and stator flux magnitude a voltage vector is selected to restricts the torque and the flux error with in their respective torque and flux hysteresis bands. In the conventional DTC, the selected voltage vector is applied for the whole switching period degraders of the magnitude of the torque error. This can result in high torque ripple. A better device performance can be achieved by varying the duty ratio of the selected voltage vector during each switching period according to the magnitude of the torque error and the position of the stator flux. A duty ratio control scheme for an inverter fed induction machine using DTC method is presented in this thesis. The use of the duty ratio control resulted in improved steady state torque response, with less torque ripple than the conventional DTC. The effectiveness of the duty ratio method was verified by simulation using SIMULINK.

KEYWORDS: DTC, Motor Terminal Voltage, SIMULINK

INTRODUCTION

Statement of the Problem

A simplified variation of field orientation known as direct torque control (DTC) was developed by Takahashi and Depenbrock. Figure 1 shows a DTC of an induction motor. In direct torque controlled induction motor drives, it is possible to control directly the stator flux linkage and the electromagnetic torque by the selection of an optimum inverter switching state.

The selection of the switching state is made to restrict the flux and the torque errors within their respective hysteresis bands and to obtain the fastest torque response and highest efficiency at every instant. DTC is simpler than field-oriented control and less dependent on the motor model, since the stator resistance value is the only machine parameter used to estimate the stator flux.

One of the disadvantages of DTC is the high torque ripple. Under constant load in steady state, an active switching state causes the torque to continue to increase past its reference value until the end of the switching period; then a zero voltage vector is applied for the next switching period causing the torque to continue to decrease below its reference value until the end of the switching period. That results in high torque ripple as shown in Figure 2(a). A possible solution to reduce the torque ripple is to use a high switching frequency;

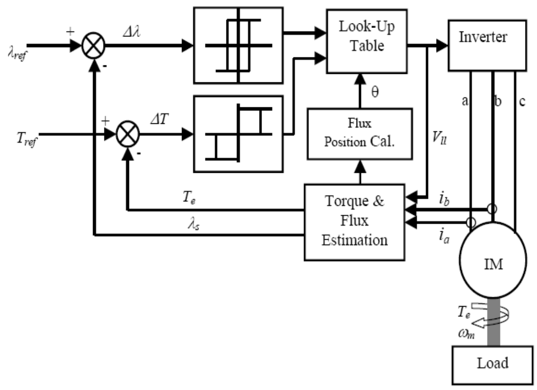


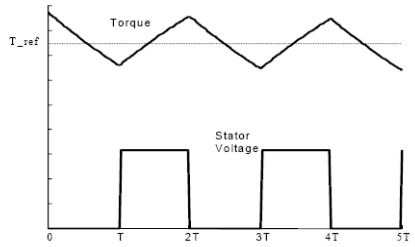
Figure 1: Direct Torque Control Scheme

However, that requires expensive processors and switching devices. A less expensive solution is to use duty ratio control. In DTC with duty ratio control, the selected voltage vector is applied for a part of the switching period rather than the complete switching period as in conventional DTC.

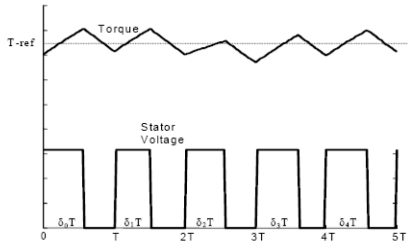
By applying a nonzero voltage vector for only a portion of the switching period, and the zero voltage vectors for the remainder of the period, the effective switching frequency is doubled. Therefore, over any single switching period, the torque variations above and below the average value are smaller, as shown `in Figure 2(b). Further, because the duty ratio is controlled, the average stator voltage is adjusted directly.

There is no need to make coarse corrections by the use of multiple switching periods with a nonzero voltage vector or a whole switching period with a zero voltage vector. The average phase voltage is adjusted more smoothly, and the overall torque ripple is reduced.

The use of a duty ratio controller is proposed in [5]. The theme of this thesis is to verify by simulation and experiment that a DTC with a duty ratio controller reduces the torque ripple compared to conventional DTC.



(a) Conventional DTC



(b) DTC with duty ratio control

Figure 2: Effect of the Duty Ratio Control on the Torque Ripple

DIRECT TORQUE CONTROL OF INDUCTION MOTOR

In DTC it is possible to control directly the stator flux and the torque by selecting the appropriate inverter state.

Its main features are as follows:

- Direct control of flux and torque.
- Indirect control of stator currents and voltages.
- Approximately sinusoidal stator fluxes and stator currents.
- High dynamic performance even at stand still locked rotor.

This Method Presents The Following Advantages:

- Absence of co-ordinate transform.
- Absence of voltage modulator block, as well as other controllers such as PID for motor flux and torque.
- Minimal torque response time, even better than the vector controllers.

DTC PRINCIPLES

It is well known that in the three-phase induction machines the electromagnetic torque can be expressed as follows [2][3]:

$$t_e = -\frac{3}{2} P \overline{\Psi_s} * \overline{i_s} \tag{1}$$

Where Ψs is the stator flux, is is the stator current (both fixed to the stationary reference frame) and P the number of pairs of poles. The previous equation can be modified and expressed as follows:

$$t_e = -\frac{3}{2} P \left|\overline{\Psi_s}\right| . \left|\overline{i_s}\right| . \sin(\alpha_s - \rho_s) \tag{2}$$

Where ρs is the stator flux angle and αs is the stator current one, both referred to the horizontal axis of the stationary frame fixed to the stator.

If the stator flux is kept constant and the angle ρs is changed quickly, then the electromagnetic torque can be changed in a fast way.

The same conclusion can be obtained using another expression for the electromagnetic torque. Firstly, the equations of the stator and rotor fluxes should be considered:

$$\overline{\psi_s} = L_s \overline{i_s} + L_m \overline{i_r}$$

$$\overline{\psi_r}' = L_r \overline{i_r}' + L_m \overline{i}_s \tag{3}$$

Both are referred again to the stationary reference frame fixed to the stator. If the stator and rotor currents are isolated, then:

$$\overline{i_s} = \frac{\overline{\psi_s}}{L_s} - \frac{L_m}{L_s} \overline{i_r}'$$

$$\overline{i_r} = \frac{\overline{\psi_r}}{L_r} - \frac{L_m}{L_r}\overline{i_s}' \tag{4}$$

Substituting the rotor current expression into the stator current expression, the next equation is obtained:

$$\overline{i_s} = \frac{\overline{\psi_s}}{L_s} - \frac{L_m}{L_s}\left(\frac{\overline{\psi_r}}{L_r} - \frac{L_m}{L_r}\overline{i_s}'\right) \tag{5}$$

And isolating the stator current again,

$$\overline{i_s} = \frac{L_r}{L_s L_r - L_m^2}\overline{\psi_s} - \frac{L_m}{L_s L_r - L_m^2}\overline{\psi_r} \tag{6}$$

Finally substituting the previous expression (6) into the equation (1), the following new expressions for the electromagnetic torque are obtained:

$$t_e = \frac{3}{2} P \frac{L_m}{L_s L_r - L_m^2} \psi_r * \psi_s \tag{7}$$

Finally, the torque expression is as follows:

$$t_e = \frac{3}{2} P \frac{L_m}{L_s L_r - L_m^2} |\psi_r|.|\psi_s|.\sin(\rho_s - \rho_r) \tag{8}$$

Because of the rotor time constant is larger than the stator one, the rotor flux changes slowly compared to the stator flux; in fact, the rotor flux can be assumed constant. (The fact that the rotor flux can be assumed constant is true as long as the response time of the control is much faster than the rotor time constant, which is usually between 0.04 and 0.1s).

As long as the stator flux will be kept constant, then the electromagnetic torque can be rapidly changed and controlled by means of changing the angle $(\rho_s - \rho_r)$ [1][3].

DTC CONTROLLER

The way to impose the required stator flux is by means of the Voltage Source Inverter state. If the ohmic drops are neglected for simplicity, then the stator voltage impresses directly the stator flux in accordance with the next equation:

$$\frac{d\psi_s}{dt} = \overline{u_s} \tag{9}$$

Or

$$\Delta\overline{\psi_s} = \overline{u_s}\Delta t \tag{10}$$

Decoupled control of the torque and stator flux is achieved by acting on the radial and tangential components of the stator flux-linkage space vector in its locus. These two components are directly proportional (Rs=0) to the components of the same voltage space vector in the same directions. Next figure 1 shows the possible dynamic locus of the stator flux, and its different variation depending on the VSI states chosen. The possible global locus is divided into six different sectors

signaled by the discontinuous line.

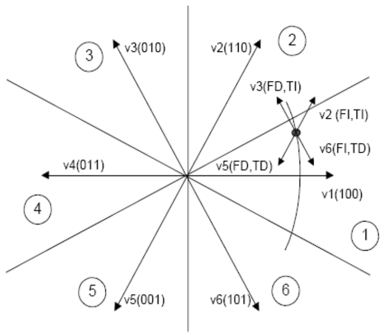


Figure 3: Stator Flux Vector Locus and Different Possible Switching Voltage Vectors. FD: Flux Decrease. FI: Flux Increase TD: Torque Decrease. TI: Torque Increase

In Accordance with the figure 1, the following general table can be written:

Table 1: General Selection Table for Direct Torque Control

IN THE k SECTOR	INCREASE	DECREASE
Stator Flux	K,k+1,k-1	k+2,k-2,k+3
Torque	K+1,k+2	k-1, k-2

It can be seen that the states k and k+3, are not considered in the Torque because they can both increase or decrease the torque at the same sector depending on if the position is in the first 30 degrees or in the second ones. The usage of these states for controlling the Torque is considered one of the points to develop in the further research dividing the total locus into twelve sectors instead of just six. Finally, if the table is developed can be obtained the following one:

Table 2: Selection Table for Direct Torque Control

Φ	τ	S_1	S_2	S_3	S_4	S_5	S_6
1	1	V2	V3	V4	V5	V6	V1
	0	V0	V7	V0	V7	V0	V7
	-1	V6	V1	V2	V3	V4	V5
0	1	V3	V4	V5	V6	V1	V2
	0	V7	V0	V7	V0	V7	V0
	-1	V5	V6	V1	V2	V3	V4

The sections of the stator flux space vector are denoted from S1 to S6. The flux error (ϕ), as it is explained in the following paragraph, can take two different values, meanwhile the torque error (τ) can take three different values. The zero voltage vectors V0 and V7 are selected when the torque error is within the given hysteresis limits.

CONCLUSIONS

Direct Torque Control is considered to be one of the best methods to drive induction motors, even better that the well-known Vector Controls. However, DTC has some disadvantages, being one of the most important the torque ripple. Further research must be focused on trying to improve this main DTC disadvantage by means of artificial intelligence methods.

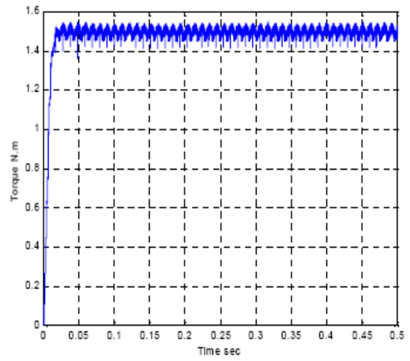


Figure 4: Electric Torque Using DTC with the Duty Ratio Control

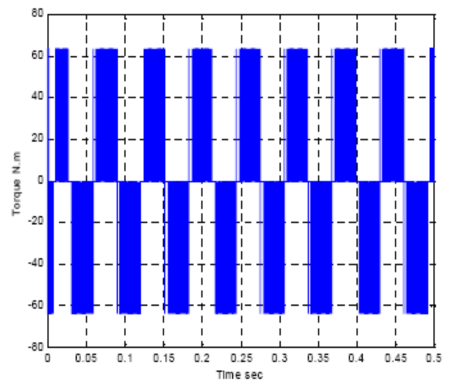


Figure 5: Stator Voltage Using DTC with the Duty Ratio Control

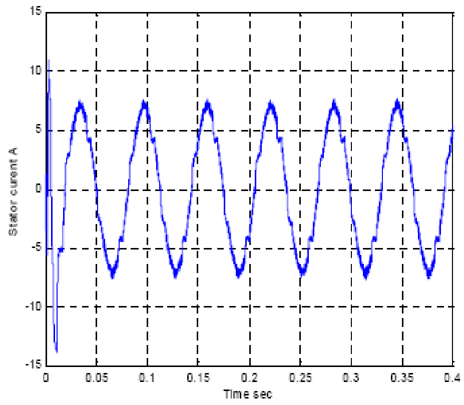


Figure 6: Stator Current Using DTC with Duty Ratio Control

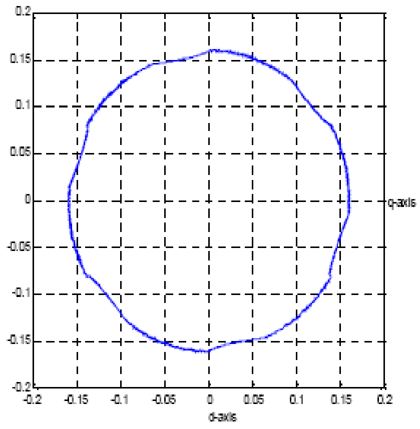


Figure 7: Stator Flux Vector Using DTC with Duty Ratio Controller at 20 Khz

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